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Analysis of Flow Characteristics of Window-Combination-Type Ventilation System Using CFD

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Abstract: In this study, we analyze the performance of ventilation modules to improve air quality in educational facilities. Using (CFD), we examine the flow design variables of a window-mounted ventilation module. Using computational analysis, we analyze various flow design characteristics of window-mounted ventilation modules and review optimal conditions. First, we measure the carbon dioxide concentration in the classroom and use CFD to analyze the internal air characteristics according to the ventilation module's inflow speed, inflow angle, and indoor temperature conditions. According to classroom air quality management standards, the concentration of carbon dioxide must be managed below 1000 ppm. When the ventilation module's inflow velocity was 2.0 m/s, a carbon dioxide concentration of less than 1000 ppm was measured in the classroom. Additionally, an air filter was selected to prevent the inflow of external fine dust through the ventilation module. The suitability of HEPA H14 was reviewed to design the weight concentration of fine dust flowing from the ventilation module to be less than 50 $\mu g/m^3$. Through research, flow design conditions for a window-mounted ventilation module were presented to reduce carbon dioxide concentration inside the classroom. The analysis of the ventilation system flow characteristics proposed in this study derived primary data for improving the classroom ventilation system.

Keywords: CO_2 concentration; air circulation; ventilation system; educational facilities

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1. Introduction

Most people live in indoor spaces for more than 80% of a 24 h day. In particular, Korean students spend more time in classrooms than in other countries [1]. The average time spent in classrooms per week is 50 h in Korea, which is about 20 h more than in other OECD countries. As the number of students in the classroom increases, the oxygen level decreases and the carbon dioxide concentration increases due to the students' breath [2]. Natural ventilation can purify indoor air [3], but particulate matter introduced through outdoor air can adversely affect indoor air quality. Currently, the "Indoor Air Quality Management Act for Multi-use Facilities, etc." in Korea stipulates that the concentration of carbon dioxide should be managed and maintained at less than 1000 ppm [4]. Generally, sleepiness starts when the indoor carbon dioxide concentration reaches 1000 ppm, and increasing blood pressure, headache, and dizziness occur when it exceeds 3000 ppm. Classrooms at domestic educational institutions use natural ventilation and mechanical ventilation. Natural ventilation or air conditioners can improve the air quality in a closed room. However, when pollutants accumulate in the room, severe problems can occur to indoor people who live with contaminated air [5]. As such, it is necessary to study the improvement in indoor air quality in order to improve the quality of health and education of students who study in the classroom of educational facilities [6–8].

Due to the recent emergence of COVID-19, interest in indoor air quality (IAQ) has increased [9]. In particular, indoor air purification solutions and technologies are continuously being developed. And we need to focus more on air quality management in educational spaces [10,11]. When carbon dioxide exceeds a certain concentration, it causes drowsiness and adversely affects not only the health of students but also their concentration in lectures [12,13]. To prevent this, confined spaces with many people need periodic ventilation as much as possible. However, this also causes a problem because air contaminated with seasonal fine dust and pollen in spring flows into the room. Recently, various studies and technologies have been proposed to improve indoor air quality (IAQ).

In order to improve indoor air quality in school classrooms, Hwan-Chul and two others developed an energy-saving interlocking control algorithm for ventilators and air purifiers. They reviewed the applicability of the developed algorithm [14].

Choi and four others developed an optimal control algorithm for ventilation systems to improve the indoor air quality of school facilities and confirmed their applicability [15].

Kanama et al. [16] analyzed indoor air quality and improved health impact assessments by measuring data that allowed occupants' exposure to be estimated. In addition, the movement of pollutants was confirmed using spatial and temporal discretization measurement methods of pollutants.

Rodero et al. [17] presented a new approach to the estimation for IAQ improvement and ventilation system design, and they measured the carbon dioxide concentration in various spaces such as classrooms, seminar rooms, and computer rooms. Based on the results, the CO_2 increase according to ACH and human age was derived.

Mata et al. [18] comprehensively reviewed indoor air quality improvement technologies. Technologies such as mechanical filtration, electronic filtration, UV photocatalytic oxidation, ionization, and biological filtration were comprehensively reviewed, and indoor air quality management was emphasized.

Lim et al. [19] assessed Energy-Efficient Housing (EEH) IAQ levels and daily health symptoms of occupants. Studies have shown that increased carbon dioxide levels are associated with symptoms of eye strain, allergic rhinitis, and atopic dermatitis. And improving IAQ has a positive impact on residents' health.

Yang et al. [20] used MATLAB to develop an IAQ prediction tool for building design. The i-IAQ tool was verified based on air pollutant measurement cases. In addition, diagnosis and recommendations were provided at the design stage to improve the IAQ of the building.

Mohamed et al. [21] studied indoor comfort and air quality in primary school classrooms in England. Monitoring variables were set, and the effects of carbon dioxide and fine dust were evaluated. Then, the carbon dioxide concentration was analyzed when the heater was used in the classroom.

Mumtaz et al. [22] analyzed indoor air quality based on the Internet of Things (IoT) from the COVID-19 perspective. Eight pollutants were measured using sensors, and a web portal and mobile app were developed based on GSM/Wi-Fi technology. They developed a system that warns when air quality abnormalities are detected.

As suggested in the study results above, the health of occupants is dominated by the indoor environment [23–26]. In addition, it is essential to analyze indoor air quality considering the characteristics of the space [27]. In this study, we propose a window-to-door combined ventilation system operated in classrooms. The ventilation system was analyzed from the perspective of flow design and designed considering the characteristics of the space (number of students, student placement, age, etc.). In this study, 52 people applied mass flow to carbon dioxide generated during breathing at each point where a person is located. In the case without the ventilation window module, the concentration of carbon dioxide increased throughout the classroom, and about 4500 ppm of carbon dioxide can be checked in 75 min. Referring to this result, it was judged that CFD simulation was sufficient because the concentration of carbon dioxide was high in the air throughout the classroom. The proposed system inflows outside air into the classroom using a fan. And a filter is installed inside to filter fine dust and pollen. The main contributions and novelties of the proposed system are as follows. First, it is efficient in the installation and operation cost through the design of flow characteristics considering the internal environment of the classroom. Second, it is a window–door combined design structure. It is installed at the top of the window and can be adjusted according to the number of occupants. And the visibility of the window is positive. Third, when natural ventilation is used to reduce indoor carbon dioxide concentration, pollutants from outside are inflowed together. However, contaminants can be filtered out using a filter.

2. Methodology

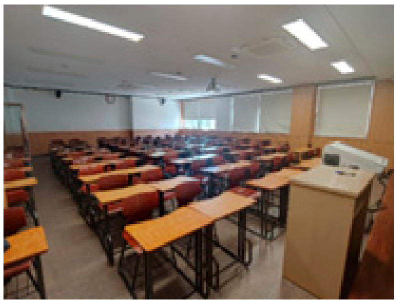
As the problem of air pollution gradually emerges, various products are being developed through research on improving air quality in the classroom. And lots of studies are conducted on the correlation between students' concentration and the concentration of carbon dioxide in the classroom. So far, no study has combined the problems of air pollution and CO_2 in classrooms. In this study, considering the purpose of the use of the space, the number of students, and characteristics of the space, the reduction in CO_2 and ventilation performance were analyzed to select the amount of optimal ventilation.

The purpose of this study is to optimize the ventilation system for classrooms. In addition, it is possible to provide a pleasant educational environment by analyzing the ventilation system according to the characteristics of the classroom. This section introduces the structure of this paper and explains the research method. Section 1 introduces the importance of improving indoor air quality, and recent research trends are explained. Section 2 introduces the proposed ventilation system research process, composition, and methodology of the thesis. Section 3 explains the experiment method and result of measuring the concentration of carbon dioxide generated in the classroom. Section 4 explains the structural characteristics of the proposed technology, and the CFD conditions, modeling, and boundary conditions for flow design are explained. Section 5 explains the classroom ventilation system design research results. Finally, Section 6 summarizes the findings, and the research conclusions and future discussions are explained.

As the domestic fine dust problem gradually worsens, government and researchers are responding to the improvement in indoor and outdoor air quality by defining it as a disaster and strengthening fine dust reduction measures and air quality management regulations. Table 1 shows the air environment standards, the School Health Act, the Indoor Air Quality Management Act, and the indoor air quality management standards for new construction houses. In the case of schools, it is stipulated that fine dust PM10 is less than 75 for teachers and food service facilities, PM2.5 is less than 35 for PM2.5, and PM10 is less than 150 for gyms and auditoriums. In school classrooms where elementary-, middle-, and high-school students spend most of their time, air quality management standards, including carbon dioxide and fine dust, are more strictly managed than multi-use facilities. Therefore, by developing a window-attached ventilation window module for the classroom, clean air flows into the classroom through a filter, and the carbon dioxide concentration generated by indoor occupants is reduced. The ventilation window module can be installed on the top of the window and consists of a total of three filter layers inside the module.

In order to analyze the carbon dioxide concentration generated in the classroom during class, the carbon dioxide concentration was measured in the classroom. The measurement equipment was AQ-9901SD, which can be measured up to 8000 ppm using a carbon dioxide sensor and was measured using measurement equipment with a resolution of 1 ppm. The measurement method was to sufficiently ventilate the classroom through natural ventilation before the lecture, and then analyze the carbon dioxide concentration at 6 indoor measurement points during the 75 min lecture. The carbon dioxide measurement location is shown in Figure 1; the corridor side (Point_1), the center of the classroom (Point_2), and the window side (Point_3) were measured based on the origin of the classroom; and the carbon dioxide results were confirmed at the central location of the classroom at 1.2 m (Point_2), the floor height (Point_4), and the ceiling height (Point_5).

Table 1. Comparison of elementary classroom and target classroom.

	Educational Facilities Classroom	**Target Classroom**
Classroom area	67.5 m^2	92.3 m^2
The number of students	24	52
Classroom area per person	2.81 m^2/people	1.77 m^2/people
Photo		

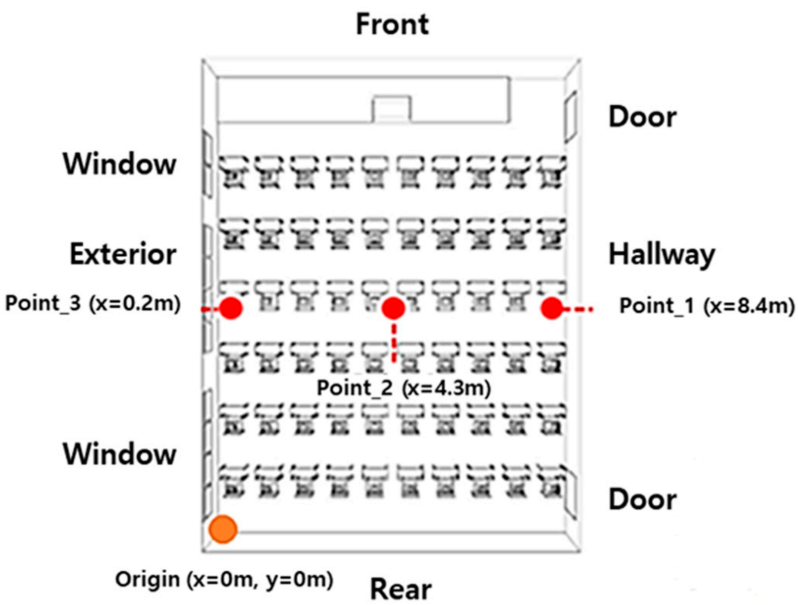


Figure 1. CO_2 measurement points in the classroom.

3. Introduction of Latest Technologies and Research

3.1. Target Classroom Selection

The target classroom was selected to perform air quality measurement and CFD analysis in the classroom of the educational institution. The selected classroom is 8.4 m × 11.0 m × 3.0 m, with a total area of about 92.3 m^2, accommodating an average of 52 students. The average classroom area per student by the elementary-, middle-, and high-school in Korea is shown in Figure 2 and Table 1 below. The light blue bar represents a typical classroom, and the orange bar represents the target classroom used in this study. According to the domestic classroom standard design, the average classroom area per student in elementary and secondary educational institutions is 2.8 m^2, and the average classroom area per person is 1.7 m^2 in the case of the target class selected in this study. Since the personnel density and carbon dioxide generation amount of the target classrooms selected for this study are higher than those of elementary and secondary educational institutions, appropriate ventilation should be secured.

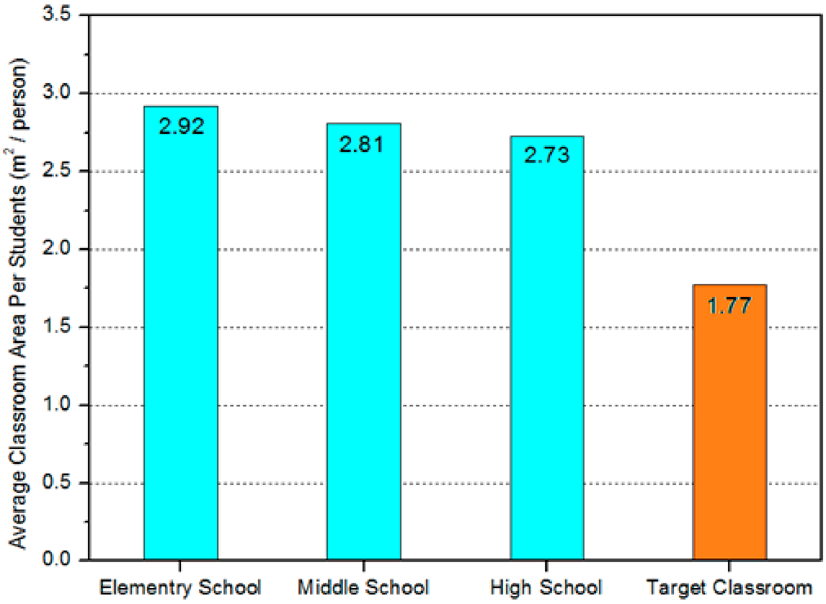


Figure 2. Average classroom area per student.

3.2. Measurement of Carbon Dioxide Concentration in the Classroom

Before performing CFD analysis, the carbon dioxide concentration was measured to confirm the carbon dioxide concentration inside the classroom. The carbon dioxide measurement location of the target class is shown in Figure 1. The measurement location inside the classroom was selected based on z = 1.2 m, which corresponds to the average height when the number of people in the room sat, and data were collected at a total of three points. In Figure 1, the red point represents the measured position, and the orange point rep-resents the origin. Six repeated measurements were performed, and the results were averaged and are shown in Figure 3 below. After the start of the measurement, the concentration continues to increase after the first 1000 ppm at Point_3, a location near the target classroom window, exceeding 2000 ppm at 1142 s at Point_3 and 2000 ppm at Point_1 and Point_2 at approximately 1500 s. Concentrations of approximately 4000 to 5000 ppm at all points are measured at the end of the class of 4500 s.

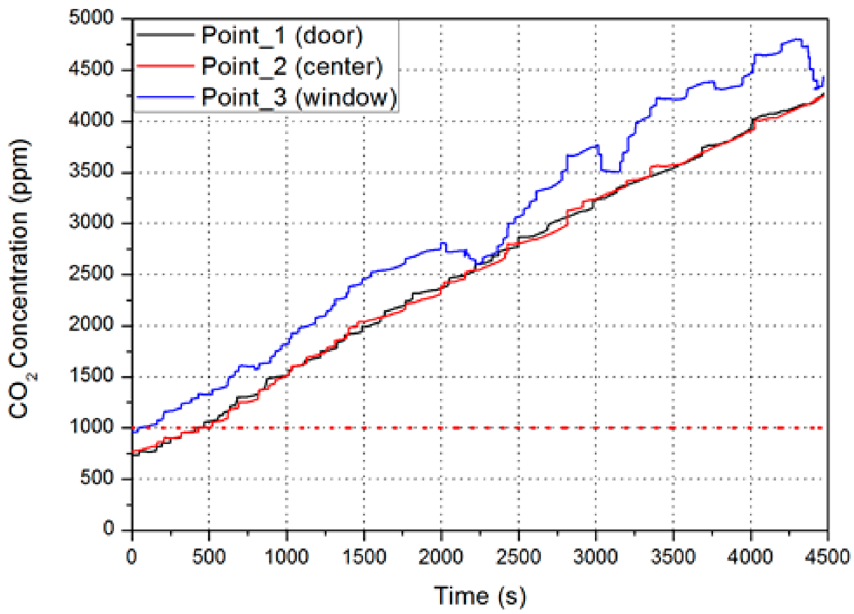


Figure 3. The measurement result of CO_2 concentration in the classroom.

4. Flow Design Analysis of Ventilation Module

4.1. CFD Analysis Method and Modeling

In this study, analysis is performed using CFD to derive the flow design conditions of the ventilation window module, which is a mechanical ventilation system of educational institutions. Figure 4 below explains the modeling shape of the classroom. Since the upper window should be set as the boundary conditions for the ventilation window module and the wall, a gap is created between the window and the door so that air can flow in and out, and a thickness of 10 mm is applied. The window size is set to 0.7 m wide and 0.4 m long. The number of people in the classroom is set to 52, and CO_2 supply is implemented so that carbon dioxide is generated at the height of the breathing line.

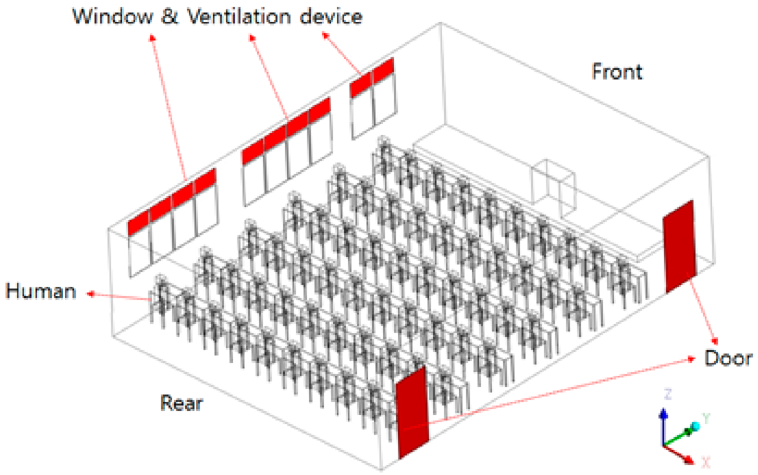


Figure 4. Classroom modeling geometry for computational analysis.

4.2. Boundary Conditions and Case Configuration

The boundary conditions are shown in Table 2 below to perform flow analysis and carbon dioxide concentration analysis in the target classroom. The concentration of carbon dioxide in a classroom is proportional to the number of students. Therefore, this study set nitrogen, oxygen, and carbon dioxide in the air. And the human respiratory flow rate was set to 1.5625×10^{-4} kg/s. The location where the ventilation window module is installed is in the upper window of the classroom and is set to Velocity inlet and Mass flow inlet according to the case. The analysis case is classified to select the flow design variable of the ventilation window module applied to the school classroom. It is classified according to the outside air inflow speed, inflow angle, and indoor temperature conditions.

Table 2. Species percentage of indoor and out-breathing and mass flow rate of out-breathing.

Analysis Models		
Viscous	Standard k-ε turbulent model	
Species	Species transport	
Energy	Energy equation	
Species rates and Mass flow inlet		
Indoor (%)	N_2	79.05
	O_2	20.90
	CO_2	0.05
Out-breathing (%)	N_2	79.70
	O_2	16.30
	CO_2	4.00
Mass flow inlet Of out-breathing (kg/s)	1.5625×10^{-4}	

Table 2. *Cont.*

Boundary conditions	
Upper window	Velocity inlet, Mass flow inlet
Door gap	Pressure outlet
Out-breathing	Mass flow inlet

Table 3 below shows the case according to the outside air inflow rate of the ventilation window module and is divided into five flow conditions: None, 0.5 m/s, 1.0 m/s, 2.0 m/s, and 3.0 m/s. As shown in Table 3 below, the case for inflow angle is composed of five types: 0° equal to 2.0 m/s, 22.5° and 45° flowing into the upper part of the classroom, and −22.5° and −45° flowing into the lower part of the classroom. The room temperature conditions are shown in Table 3. They are 5.0 °C, 20.0 °C, and 35.0 °C. In both the inflow angle and indoor temperature conditions, outside air flows at a rate of 2.0 m/s.

Table 3. Case classification for computational analysis.

Case	**Inlet Velocity (m/s)**	**Remark**
Case_V0	None	
Case_V1	0.5	• Temperature: 20.0 °C
Case_V2	1.0	• Inlet angle: 0°
Case_V3	2.0	• Number of ventilation modules: 10
Case_V4	3.0	
Case	**Inflow angle (°)**	**Remark**
Case_A1	0	
Case_A2	−45.0	• Inlet velocity: 2.0 m/s
Case_A3	−22.5	• Temperature: 20.0 °C
Case_A4	22.5	• Number of ventilation modules: 10
Case_A5	45.0	
Case	**Temperature (°C)**	**Remark**
Case_T1	5.0	• Inlet velocity: 2.0 m/s
Case_T2	20.0	• Inlet angle: 0°
Case_T3	35.0	• Number of ventilation modules: 10

5. Results and Discussion

5.1. Results of Flow Behavior and Ventilation Rate

The CFD analysis was applied to select the flow design conditions of the ventilation window module to improve the air quality of the classroom. Ansys Fluent 19ver was used for CFD analysis [28,29]. When the velocity of the inlet of the ventilation window module is relatively low, 0.5 m/s (Figure 5a), the entire classroom is a congested area. As the flow rate increases, the recirculation area in the classroom expands. When the velocity of the inlet is 2.0 m/s or higher, the whole classroom area is well ventilated. The results of analyzing the ventilation rate and ACH (air changes per hour) [30] of the classroom that installed the ventilation window module are shown in Table 4. According to the standard ventilation rate of domestic schools, the standard ventilation rate is 21.3 m^3/h in the classroom, and in the case of selected university classrooms, it is 1123.2 m^3/h. All cases meet the standard ventilation rate in the classroom.

Table 4. Flow rate and ventilation frequency for each analysis case

Case	**Ventilation Volume (m^3/h)**	**ACH**
Case_V1	4916.32	17
Case_V2	9808.57	34
Case_V3	20,219.58	41
Case_V4	30,310.93	106

Table 4. *Cont.*

Case	Ventilation Volume (m^3/h)	ACH
Case_A1	20,219.80	71
Case_A2	20,214.10	71
Case_A3	20,213.33	71
Case_A4	20,222.13	71
Case_A5	20,223.10	71

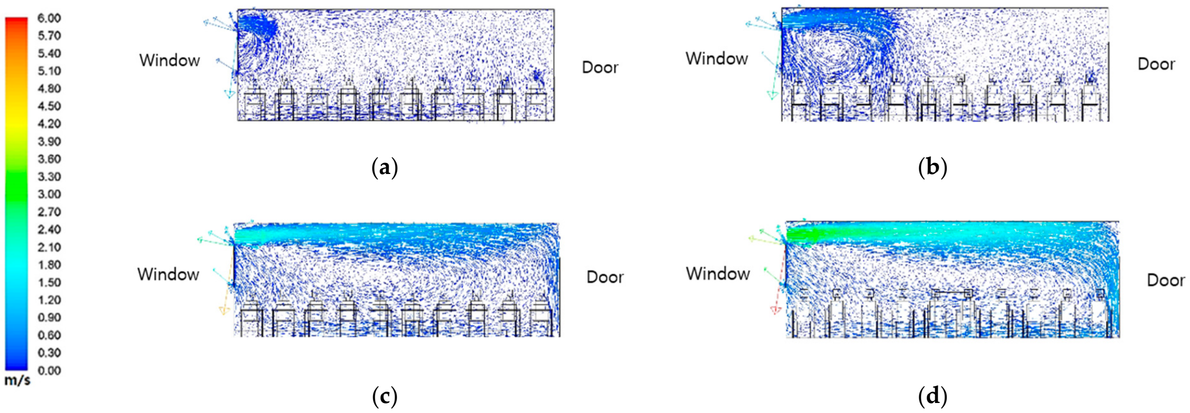


Figure 5. Average classroom area per student: (**a**) velocity of inlet, 0.5 m/s; (**b**) velocity of inlet, 1.0 m/s; (**c**) velocity of inlet, 2.0 m/s; (**d**) velocity of inlet, 3.0 m/s.

5.2. Results of the CO_2 Concentration in the Classroom

The analysis results when the ventilation window module is not installed are shown in Figure 6. In the figure, the standard value of 1000 ppm is indicated by a dotted line. From about 700 s, it exceeds the legal standard of 1000 ppm, and from about 1700 s, it exceeds 2000 ppm. At 3000 s, it exceeds 3000 ppm. The highest concentration of carbon dioxide measured rises to approximately 4100 ppm. And even after that, if there is no ventilation, the concentration of carbon dioxide will continue to increase and affect people.

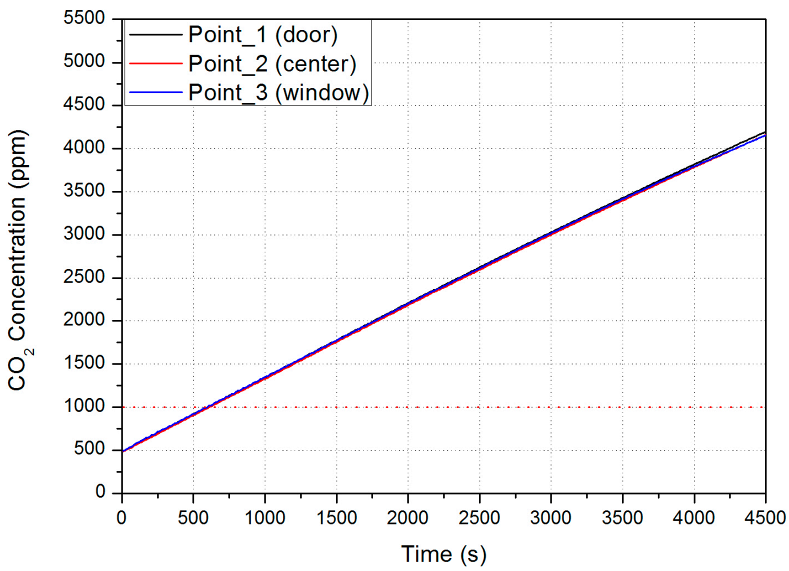


Figure 6. CO_2 concentration results of Case_V0.

When not ventilated, the CO_2 concentration will continually increase, judged to affect people. The CO_2 concentration converged at 4450 s, and the results of CO_2 concentration at

4450 s when the ventilation window module was installed are shown in Figure 7. In the figure, the dotted line represents the standard value, 1000 ppm. In the case of Case_V1, the CO_2 concentration of Point_1 was 1150 ppm; as it exceeds the national legal standard value of 1000 ppm, it is not a suitable case. In the case of Case_V2, the CO_2 concentration of Point_3 was 550 ppm, which was relatively low, but the CO_2 concentration was not stable at the other points (Point_1 and Point_2). Therefore, this condition is also not suitable. The CO_2 concentration of Case_V3 was low compared to Case_V1 and V2. Also, it was stable at all points. Accordingly, the ventilation window module in the case of Case_V3 (2.0 m/s) is suitable. Figure 8 shows the results according to the inflow angle when the ventilation window module was installed. According to the inflow angle, the results were confirmed at 4450 s when the CO_2 concentration converged. The CO_2 concentration under the −45.0° condition was lower than those of the 0° and 45.0° conditions except for Point_2. There was not much difference, but in the case of −45°, the concentrations of Point_2 and Point_3 differed by about 100 ppm, and the overall CO_2 concentration was uneven. Conversely, in the case of −4.0°, the concentration was stable for all three points. Overall, the concentration was maintained at about 500 ppm. This confirmed that the outside air intake angle did not significantly affect indoor air quality improvement. The results according to the indoor temperature conditions are shown in Figure 9. According to the indoor temperature, the results are confirmed at 4450 s when the CO_2 concentration converges. At Point_2 and 3, the CO_2 concentration at all temperatures is similar, and at Point_1, the CO_2 concentration decreases as the temperature increases. In all indoor temperature conditions, there is no case exceeding the standard value of 1000 ppm, so the change in CO_2 concentration according to indoor temperature conditions is insignificant.

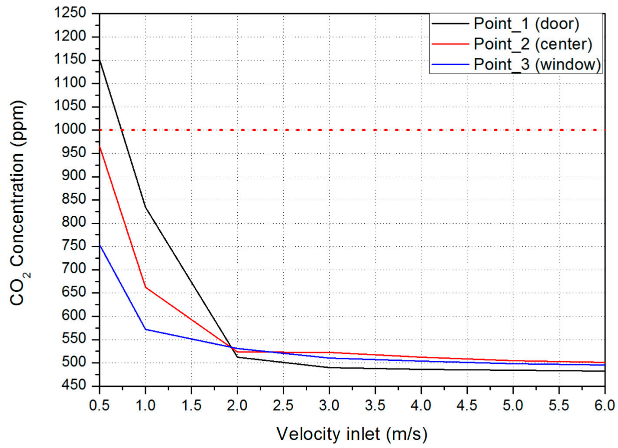


Figure 7. CO_2 concentration results of velocity.

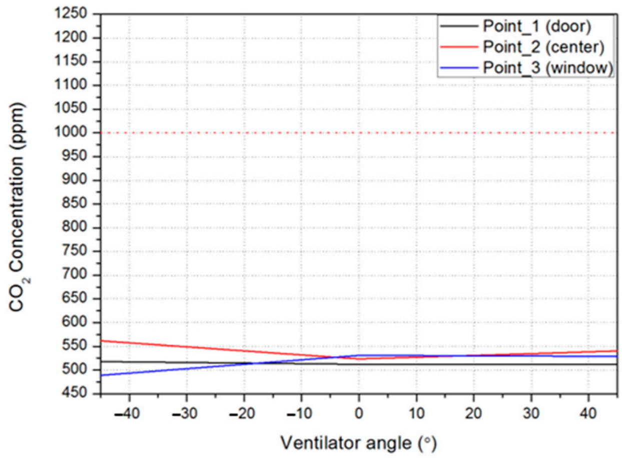


Figure 8. CO_2 concentration results with angle.

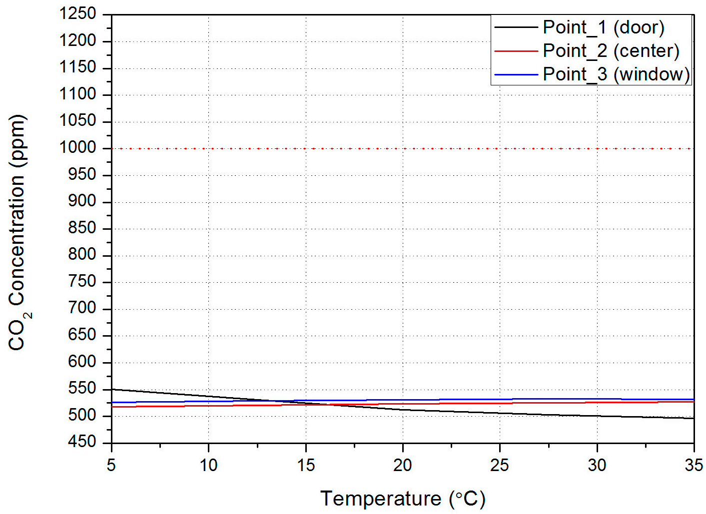


Figure 9. CO_2 concentration results of indoor temperature.

The amount of human inhalation through breathing varies depending on their surroundings, but it generally contains 79.00% N_2, 20.90% O_2, and 0.05% CO_2. Since only about 5% of the 20.9% O_2 introduced into the human body through inhalation is used and discharged into exhalation, the components of exhalation were analyzed by applying 79.7% N_2, 16.3% O_2, and 4.00% CO_2. An analysis of indoor CO_2 concentration characteristics was conducted using CFD to select the capacity of the fan of the ventilation window module, and the analysis results are shown in Table 5. Case_V0 without the ventilation window module increased the concentration of CO_2 throughout the classroom, and about 4500 ppm of CO_2 was confirmed in 75 min. In the case of 0.5 m/s of outside air inflow speed of the ventilation window module, the CO_2 concentration was maintained at about 2500 ppm due to the recirculation area, but it was confirmed that the CO_2 concentration was maintained above the CO_2 standard concentration, and in the case of 1.0 m/s, the area adjacent to the ventilation system was maintained at less than 1000 ppm, but the CO_2 concentration was maintained at 2500 ppm in the area adjacent to the corridor where the flow was not circulated throughout the classroom. In the case of 2.0 m/s, it was confirmed that the CO_2 concentration was maintained below 1000 ppm in all areas of the classroom for 75 min, converging to a stable concentration.

5.3. Selection of the Ventilation Window Module Filter and Ventilation Performance Analysis

5.3.1. Air Pollution Level and European Certification Standards Air Filter

When the ventilation window module is operating, an air filter is selected to reduce particulate matter inflow through the outside air. The current state of particulate matter pollution in cities in Korea was investigated to select a suitable filter. Based on particulate matter PM10 and PM2.5 air pollution data, the city with the highest pollution level was Sejong City, which recorded 71 $\mu m/m^3$ for PM10 and 47 $\mu m/m^3$ for PM2.5 in March 2019. The highest month was March, and PM10 recorded 62.33 $\mu m/m^3$ and PM2.5 recorded 38.78 $\mu m/m^3$. Therefore, this study selected the filter of the ventilation window module by applying the particulate matter concentration in Sejong City, where the highest air pollution level was measured in March 2019. The air filter was selected based on the design criterion of less than 50 of particulate matter inflow by following the CE certification standard, in Table 6. CNE EN779 class [31]. Inflow of particulate matter according to air filter grade is shown in Tables 7 and 8.

Table 5. Distribution of CO_2 concentration by flow rate.

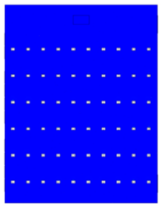
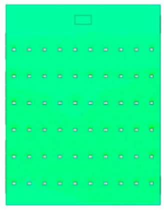
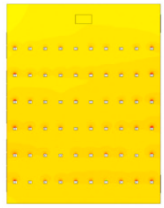
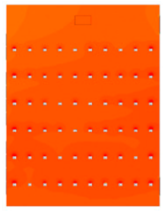
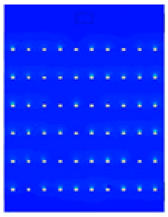
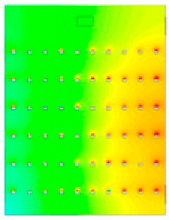
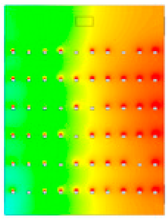
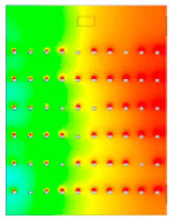
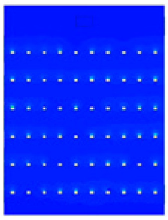
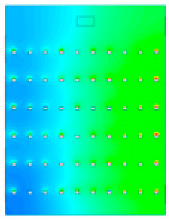
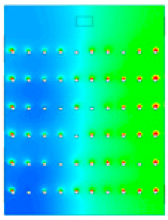
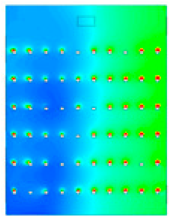
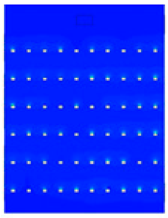
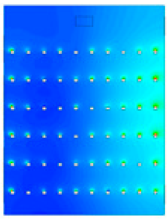
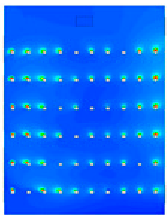
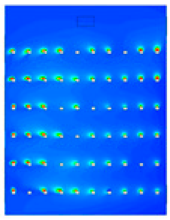
Time	0 s	2000 s	4000 s	4500 s
Case_V0 (None)				
Case_V1 (0.5 m/s)				
Case_V2 (1.0 m/s)				
Case_V3 (2.0 m/s)				

Table 6. Classification of air filter based on European certification.

Type	CEN EN779 Class	Efficiency (%)	Particulate Size	Test Standard
Coarse dust filter (Primary filter)	G1~G4	>90	>5.0 μm	BS EN779
Coarse dust filter (Secondary filter)	M5	40 < 60		
	M6~M7	40 < 90	>2.0 μm	
	F8~F9	90 < 95	>1.0 μm	
High-efficiency particulate air filter (semi-HEPA, HEPA)	E10	85		BS EN1822 [32]
	E11	95	>0.5 μm	
	E12	99.5		
	H13	99.95	>0.3 μm	
	H14	99.995		
Ultra-low-penetration air filter (ULPA)	U15	99.9995		
	U16	99.99995		
	U17	99.999995		

Table 7. Inflow of particulate matter according to air filter grade (PM10).

Type	CNE EN 779 Class	Air Filter Efficiency (%)	PM10 Weight (μg)	Indoor PM10 Concentration (μg/m³)
			$W_{PM10} = PM10_{atm}Q_{total}t$	$PM10_{indoor} = \frac{W_{PM10}(100-eff_{filter})}{V_c}$
High-efficiency particulate air filter (HEPA)	E10	85	536,760	27,863.37
	E11	95		9287.79
	E12	99.5		928.77
	E13	99.95		92.88
Ultra-low-penetration air filter (ULPA)	H14	99.995		9.30
	U15	99.9995		0.93
	U16	99.99995		0.09
	U17	99.999995		0.00

Table 8. Inflow of particulate matter according to air filter grade (PM2.5).

Type	CNE EN 779 Class	Air Filter Efficiency (%)	PM2.5 Weight (μg)	Indoor PM2.5 Concentration (μg/m³)
			$W_{PM2.5} = PM2.5_{atm}Q_{total}t$	$PM2.5_{indoor} = \frac{W_{PM2.5}(100-eff_{filter})}{V_c}$
High-efficiency particulate air filter (HEPA)	E10	85	335,320	18,444.78
	E11	95		6148.26
	E12	99.5		613.47
	E13	99.95		61.47
Ultra-low-penetration air filter (ULPA)	H14	99.995		6.15
	U15	99.9995		0.6
	U16	99.99995		0.06
	U17	99.999995		0.00

5.3.2. Selection of the Air Filter of the Ventilation Window Module

The air filter of the ventilation window module was selected by applying the particulate matter concentration of Sejong City, which had the highest particulate in 2019. The design flow rate (Q_{vent}) of the classroom ventilation window module is 0.56 m^3/s. For smooth emission of CO_2 in the classroom, it was confirmed through CFD analysis that more than three ventilation window modules should be installed.

Therefore, the total flow rate (Q) of the ventilation windows required to reduce CO_2 in the classroom is 1.68 m^3/s. And for 75 min of lecture time (t), the total amount of particulate matter (PM_{indoor}) is as follows.

$$W_{PM} = PM_{atm}Q_{vent}t$$

When operating the ventilation window module with the air filter applied for 75 min of lecture time, the weight concentration (W_{PM}) of particulate matter into the classroom through outdoor air is as follows, where eff_{filter} is the air filter's efficiency and V_c is the volume of the target classroom.

$$PM_{indoor} = \frac{W_{PM}\left(100 - eff_{filter}\right)}{V_c}$$

Based on the total amount of particulate matter PM10 and PM2.5 entering through the ventilation window module, the amount of particulate matter inflow in the classroom was derived for each air filter class of the CE certification standard, shown in Figures 10 and 11. In the figure, the red text represents the values that are higher than the target value, and the blue text represents the values that are lower than the target value. In the case of particulate matter PM10, when using the semi-HEPA filters E10, E11, and E12 and the HEPA filter H13, the weight concentration of particulate matter exceeds the target weight concentration, 50 μg/m^3, and the weight concentration of indoor particulate matter when using the HEPA filter H14 decreases to 9.30 μg/m^3.

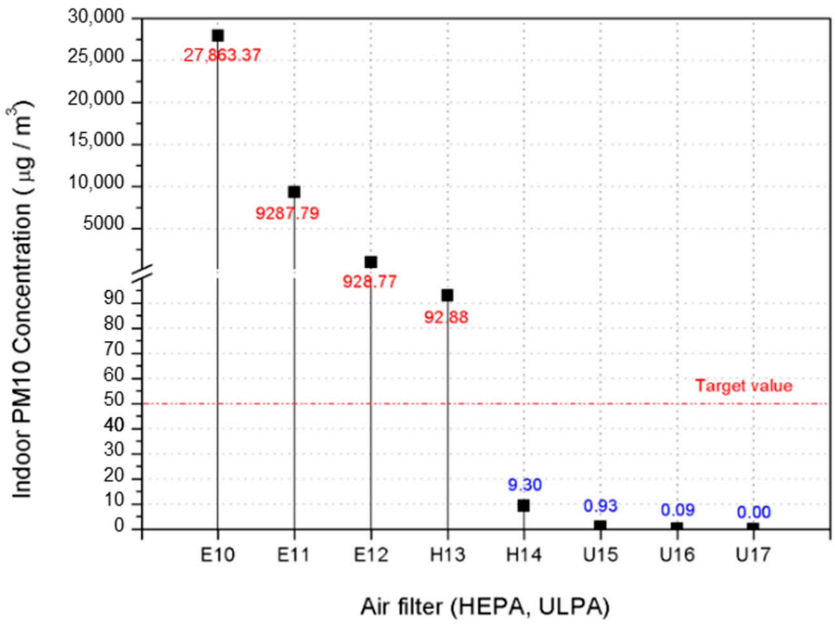


Figure 10. Particulate matter concentration according to air filter (PM10).

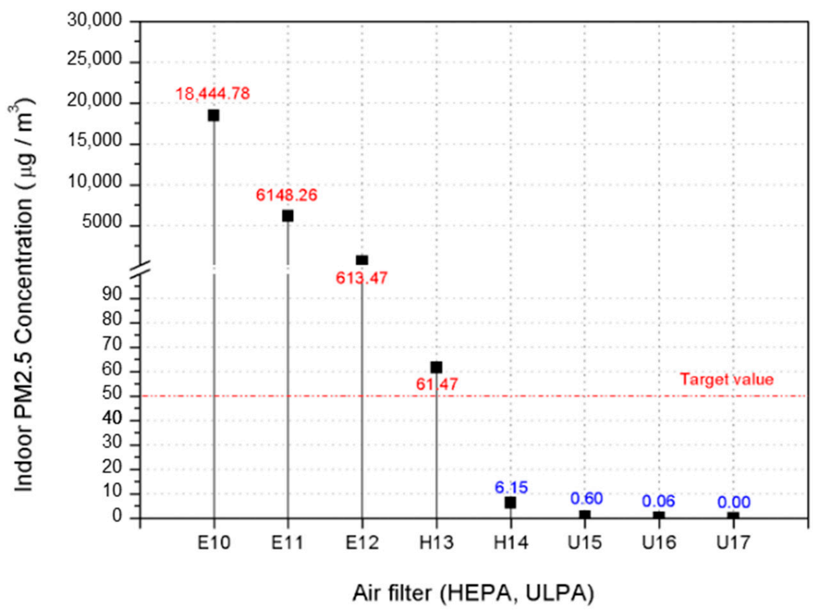


Figure 11. Particulate matter concentration according to air filter (PM2.5).

In the case of ultra-particulate matter PM2.5, the weight concentrations of inflowing particulate matter of E10, E11, E12, and H13 are all above the target weight concentration, and in the case of HEPA filter H14 and the ULPA filter U-class air filter, indoor particulate matter concentrations are below the target weight concentration.

6. Conclusions

In this study, the concentration of carbon dioxide was measured during class at an educational institution, and the flow and carbon dioxide concentration were analyzed using CFD, commercial software for heat flow analysis.

The conclusions obtained through this study by performing an appropriate flow design of the ventilation window module are as follows. The carbon dioxide concentration in the classroom selected as the measurement target was continuously measured. Based on the 75 min class, the carbon dioxide concentration generated by the number of people in the room is more than 4000 ppm after 75 min. Based on the results of the carbon dioxide concentration in the educational institution, the flow design conditions of the ventilation window module to improve air quality were derived. If the outside air inflow flow rate is less than 2.0 m/s, the circulation area in the classroom does not expand. Therefore, in the case of long-term lectures, the appropriate outside air inflow rate through the ventilation window module is 2.0 m/s to reduce the carbon dioxide concentration inside the classroom. And it was confirmed that the outside air inflow angle and internal temperature do not significantly affect the change in indoor carbon dioxide concentration characteristics. When operating the ventilation window module, an air filter that satisfies the design target of 50 $\mu g/m^3$ was selected to reduce particulate matter introduced through the outside air. When the ventilation window module was operated at Korea's highest air pollution concentration, the particulate matter concentration flowing into the room was analyzed. As a result, it was determined that applying a HEPA filter H14 or higher can reduce the concentration of particulate matter introduced from the outside.

This study examined the flow characteristics of ventilation systems to improve air quality in classrooms. Classrooms have high student density. Therefore, air quality management is essential. The analysis of the ventilation system flow characteristics proposed in this study derived primary data for improving the classroom ventilation system. Therefore, it can be used as primary data for ventilation system technology applying an IoT-based control system.

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